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Reflectivity studies of trion (X^-) and exciton (X) states in ZnSe/(Zn,Mg)(S,Se) QWs

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Abstract. The oscillator strength of negatively charged exciton (trion) in ZnSe/(Zn,Mg)(S,Se) quantum-well structures with n-type modulation doping is studied by reflection spectroscopy as a function of electron concentration and temperature. The trion oscillator strength is found to increase linearly with increasing electron concentration up to 6×10^{10} cm^{-2}. The effect of oscillator strength "shearing" between the exciton and trion states is observed. The value of the oscillator strength shearing is found to be not more than 20%.

Introduction

The existence of negatively charged exciton complexes (trions) in semiconductors, consisting of an exciton attracting an additional electron was predicted theoretically in 1958 [1]. These states have been under intensive study since 1993, when a first experimental proof of the trion existence in quantum well (QW) structures was published [2]. Trions have been observed in QW structures based on different semiconductor compounds, such as CdTe [2], GaAs [3] and ZnSe [4, 5]. However, quite a number of features of the trion states are not understood yet and/or are the subject for controversy.

This paper is concerned with the problem of the trion and exciton oscillator strengths in QW structures with high electron concentration, when the Fermi energy of 2DEG is comparable with the trion binding energy. A possibility for a redistribution of the oscillator strength between the exciton and trion with increase of the 2DEG density is mentioned in the papers [6, 7]. Authors call this redistribution as oscillator strength "shearing". However, any quantitative analysis of the observed evolution of the exciton and trion oscillator strengths as well as an understanding of the effect is still missing.

1. Modification of X^- and X states with electron concentration

We chose modulation doped ZnSe/(Zn,Mg)(S,Se) single quantum well structures as a model system for the present study. The choice of ZnSe-based QWs with extremely strong Coulomb interaction, as compared with GaAs- or CdTe-based QWs, allows us to get very pronounced exciton and trion resonances and to evaluate parameters with high experimental accuracy.

The structures with $ZnSe/Zn_{0.89}Mg_{0.11}S_{0.18}Se_{0.82}$ single quantum well (SQW) of 80 Å width were grown by molecular-beam epitaxy on (100) GaAs substrates (for details of growth and optical properties see Ref. [5]). One structure was nominally undoped and had a residual electron concentration of $n_e < 10^{10}$ cm^{-2} in the SQW. A set of modulation-doped structures with 2DEG concentration in the range from $n_e = 3\times10^{10}$ cm^{-2} up to

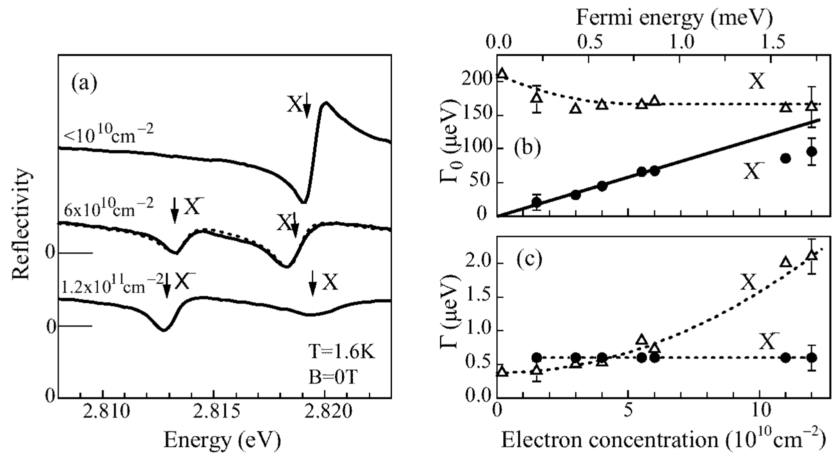

Fig. 1. (a) Reflectivity spectra taken from 80 Å ZnSe/$Zn_{0.89}Mg_{0.11}S_{0.18}Se_{0.82}$ SQWs with different electron concentrations at $T = 1.6$ K. Arrows indicate the resonance energies of excitons (X) and trions (X^-). (b) Radiative (Γ_0) and (c) nonradiative (Γ) damping for the X and X^- states as a function of the electron concentration. Dotted lines are given as guides to the eye. Solid line is calculated using Eq. (1).

1.2×10^{11} cm^{-2} were grown with a Cl doped layer separated from the QW by a 100 Å-thick spacer.

Figure 1 (a) shows reflectivity spectra in the vicinity of exciton and trion resonances taken from QW structures with different 2D electron concentrations. Details of identification of the trion transitions and basic trion properties in ZnSe-based QWs were published in Refs. [4, 5]. For the nominally undoped sample (upper spectrum) there is only one resonance line which corresponds to a heavy-hole exciton (X) in the QW. In the doped sample (middle spectrum), a new resonance line of a negatively charged exciton (X^-) appears at about 5 meV to low-energy side from the exciton one. The amplitude of the trion resonance line grows with increasing of electron concentration. At the same time this is accompanied by the reduction of exciton-resonance amplitude. At high electron concentration the exciton line disappears from the reflectivity spectra at all.

Parameters of the exciton- and trion resonances (i.e. resonance frequency, radiative damping (Γ_0) and nonradiative damping (Γ)), which govern their contribution to the dielectric function, were deduced from the best fit of experimental reflectivity spectra with the calculated ones in the framework of the non-local dielectric response theory [8]. An example of such fit is shown by the dotted line in Fig. 1(a). The electron concentration in the QW was determined from magnetoreflectivity spectra. The details of method for determination of 2DEG density are presented in Ref. [9]. The dependence of the deduced parameters as radiative (Γ_0) and nonradiative (Γ) damping of the excitons and trions are plotted against the 2DEG concentration in Figs. 1(b) and 1(c).

One can see in Fig. 1(b) that the radiative damping of the trion (Γ_0^T) increases linearly with electron concentration increases up to $n_e = 6 \times 10^{10}$ cm^{-2}. Note (following book [8]) that the exciton radiative damping Γ_0 in the QW is proportional to the exciton oscillator strength (F_X), [10] i.e. $\Gamma_0 \propto F_X$. We can introduce the trion oscillator strength per one electron (Γ_0^T/N_e), and the exciton oscillator strength per unit cell Γ_0^X/N). Here N_e is the number of electrons in the QW, N is a number of unit cells in the square of the QW.

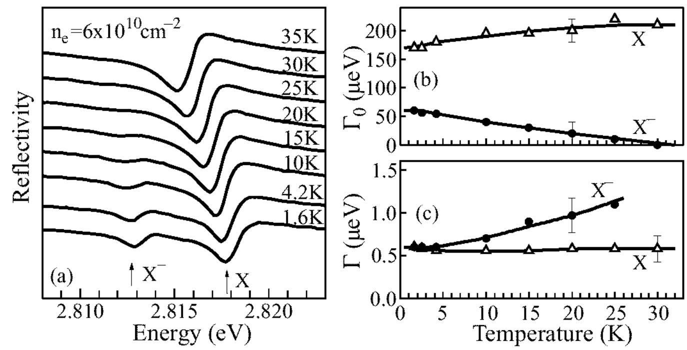

Fig. 2. (a) Reflectivity spectra taken from 80 Å $ZnSe/Zn_{0.89}Mg_{0.11}S_{0.18}Se_{0.82}$ SQWs with $n_e = 6 \times 10^{10}$ cm^{-2} at different temperatures. Arrows indicate the resonance energies of excitons (X) and trions (X^-). (b) Radiative (Γ_0) and (c) nonradiative (Γ) damping for the X and X^- states as a function of the temperature. Solid lines are given as guides to the eye.

Following the approach developed in Ref. [10] we obtain the relation:

$$\frac{\Gamma_0^T}{N_e A_T} = \frac{\Gamma_0^X}{Na} \quad \text{or} \quad \frac{\Gamma_0^T}{\Gamma_0^X} = \pi a_T^2 \cdot n_e. \tag{1}$$

Here $A_T = \pi a_T^2$ is the area with trion radius a_T, a is the area of the unit cell, $Na = A$ is the area of the QW and $N_e/A = n_e$ is the two dimensional electron concentration. Putting in Eq. (1) the experimentally determined parameters $\Gamma_0^X(n_e = 0) = 210$ μeV and $\Gamma_0^T/n_e = 1.16 \propto 10^{-9}$ μeV $\cdot$ cm^2 we evaluate the radius of the trion as $a_T = 132$ Å.

The exciton radiative damping decreases in 20% at low electron concentrations in the interval from 10^{10} cm^{-2} to $3 \propto 10^{10}$ cm^{-2} and conserves at further concentration increases. This decrease of radiative damping could be attributed to the “intensity sharing” between exciton and trion resonances suggested in Ref. [6].

Let us now turn to the nonradiative damping, which is contributed by homogeneous and inhomogeneous broadening of resonant states. For the trions the nonradiative damping Γ^T shows no concentration dependence in the range studied [Fig. 1(c)]. The possible explanation is that the trions are created predominantly in localized states and that Γ^T is dominated by inhomogeneous broadening.

Fig. 2(b) shows that the nonradiative damping of excitons increases strongly with electron concentration increase. We suggest that the exciton–electron scattering with pair excitations (when an electron is excited above the Fermi energy and hole remains inside the Fermi sea) is responsible for this effect. In that case a homogeneous contribution to the exciton line-width should be either of the order or higher than of ε_F. Namely, due to this very large exciton-line-broadening at high electron concentration the exciton line goes out from the reflectivity spectra.

2. Modification of X^- and X states with temperature

A set of reflectivity spectra registered from SQW with $n_e = 6 \times 10^{10}$ cm^{-2} is shown in Fig. 2(a) for different temperatures in the interval 1.6–35 K. As temperature increases the trion reflectivity line disappears and the amplitude of the exciton line, on the contrary, increases. Radiative and nonradiative damping for exciton and trion states are plotted in Figs. 2(b), (c) as a function of temperatures. There is no temperature effect on the exciton

nonradiative damping, at the same time a remarkable broadening of the trion line is observed in these dependencies [Fig. 2(c)]. This temperature induced broadening could be attributed to the temperature delocalization of trions.

The trion radiative damping decreases with the temperature increase [Fig. 2(b)]. That is quite understandable because the corresponding matrix element of the optical transition is maximal for small electron energy [11] and falls down rapidly with the electron energy increase. However, the temperature increasing of the exciton radiative damping is very surprising. The value of this increase is just the same as we have in the Fig. 1(b) for the exciton oscillator strength suppression by 2DEG. It could mean that the effect of the oscillator strength "shearing" is present and the value of this "shearing" is about 20% of the initial exciton oscillator strength. The physical reason for such "shearing" could be connected with an interaction between exciton and trion states via emission and absorption of an electron. A trion can lose an electron transforming into an exciton; an exciton can trap an electron transforming into a trion and so on. Such "exchange" by an electron means the interaction between these two states that could lead to some redistribution between the exciton and trion oscillator strengths.

3. Conclusions

Reflectivity spectra have been analyzed in detail for n-type modulation-doped ZnSe/(Zn,Mg)(S,Se) quantum well structures. Exciton and trion parameters were determined as a function of 2DEG density and temperature. A relation between exciton and trion oscillator strengths has been established. A linear dependence of the trion radiative damping on 2D-electron concentration has been found. The effect of oscillator strength "shearing" is directly measured.

Acknowledgements

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